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Towards an FPGA-Accelerated Programmable Data Path for Edge-to-Core Communications in 5G Networks

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Abstract

The Fifth-Generation (5G) networks, as the emerging next generation mobile networks, are adopting softwarization and virtualization technologies as the cornerstones for the network operators to gain significant competitive advantages by reducing both capital and operational expenditure, enabling agile and flexible service creation and deployment, among others. Meanwhile, a virtualized and softwarized 5G network would suffer from downgraded system performance due to this unprecedented paradigm shift towards software-based networking. Addressing one of the top challenges in this context, this paper focuses on improving the performance of the data plane from the edge to the core network segment (backhaul) in a 5G multi-tenant network by leveraging and exploring the programmability introduced by software-based networking. A fully functional prototype has been designed and implemented utilizing a Field Programmable Gate Arrays (FPGAs) acceleration-based platform, and the prototyped system has been empirically tested and evaluated to demonstrate the superior performance enhancements. The proposed solution can effectively support 5G networks in delivering mission-critical or time-sensitive applications such as ultra-high definition video use cases as experimentally validated and shown in this paper, by fulfilling the strict Quality of Service (QoS) requirements imposed to the data plane.

Keywords: Data Path, FPGA, 5G, Mobile Edge Computing, Reconfigurable hardware, Network Architecture and Design

1. Introduction

The emerging Fifth-Generation (5G) networks are expected to achieve superior performance defined in a number of Key Performance Indicators (KPIs). For instance, as far as latency is concerned, the Next Generation Mobile Networks (NGMN) Alliance [1] has defined two relevant 5G KPIs in terms of maximum latency allowed, which are 10ms and 1ms for normal traffic and extremely low latency traffic, respectively.

The usage of general-purpose Commercial Off-The-Shelf (COTS) computers at the edge of the network, together with the imposed requirements of softwarization and multi-tenant virtualization, implies that a massive portion of the data processing of the 5G architecture will be implemented in the software stack, either in the kernel or in the user space of the operating system deployed in these COTS computers. Meanwhile, these requirements are directly against the ambitious 5G KPIs imposed due to the overhead associated to the software and virtualization layers in comparison with hardware speed, and it is imperative to address a synergy where hardware and software can work together to face the new challenges introduced by 5G.

A 5G network consists of a Radio Access Network (RAN) segment, an Edge segment and a Core segment. This research work is focused on the network that interconnects Edge and Core segments. The Core network segment is typically deployed in the data center governed by a cloud computing stack

allowing multi-tenancy isolation and softwarization, whilst the Edge segment is managed by a mobile edge stack to extend both multi-tenancy and softwarization to this Point of Presence (PoP) of the network. Novel 5G Mobile/Multi-access Edge Computing (MEC) architectures [2] are proposed to deploy services in the last mile, i.e., close to the antenna and the 5G User Equipment (UE), to achieve very low delays, thereby enabling new delay-constrained real-time services.

However, there is a clear need to advance the state of the art and provide hardware-accelerated data path for the much more demanding requirements posed by the 5G architectures deployed on top of multi-tenant cloud infrastructure to achieve the expected 5G KPIs.

When a traditional Network Interface Card (NIC) receives 5G multi-tenant network traffic, it is not able to classify this traffic properly due to the unknown nested encapsulation present in the packet and thus the following consequences take place. Firstly, the programmability of this NIC can not be explored to program the hardware data plane for the 5G multi-tenant network traffic to meet security or Quality of Service (QoS) requirements, and any other value-added requirements that need hardware-acceleration to achieve the ambitious 5G KPIs. Secondly, the NIC is not able to classify the large number of different flows that are being aggregated under the same encapsulation protocol and thus not able to perform traffic engineering actions over them. Thirdly, features related to network scalability such as Receiver Side Scaling (RSS) or Transmitter Side Scaling (TSS) will not work properly since they depend on a proper classification to assign different flows to different CPU

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55 cores to scale up flow management. Our contribution in this paper is focused on overcoming these limitations.

The main contribution of this research work is to provide an insightful understanding of the 5G network communication traffic patterns envisioned between the Edge and Core segments and realize empirical implementation to achieve a hardware-accelerated data path based on Field Programmable Gate Arrays (FPGAs) for these new communication patterns. The proposed framework allows the programmability of the data path directly on the hardware to offload the software stack and thus optimizes the new 5G multi-tenant communication patterns while minimizing significantly the delay introduced by software-based solutions. Furthermore, an intensive empirical validation has been performed to demonstrate the viability and scalability of the proposed framework.

70 The rest of the paper is organized as follows. Section 2 reviews the state of the art on existing software- or hardware-based data paths. Section 3 describes the proposed FPGA-accelerated multi-tenant 5G architecture with a detailed explanation of the integral 5G elements, especially the cloud-based platform with MEC and the programmable data paths. Subsequently, section 4 presents the technical details on the prototyping of the novel FPGA-accelerated 5G programmable data path and the various challenges addressed. Section 5 describes the testbed deployed to validate the claims of this contribution and presents both performance and scalability test results to illustrate our findings. Finally, sections 7 and 8 provide further discussions and conclusions respectively.

2. Related Work

From the data path perspective, virtualization and softwarization adopted by 5G networks introduces multiple encapsulations to the application traffic and thus extra processing overhead to traffic engineering. Therefore, regarding hardware-based solutions, a pipeline with re-configurable match and action stages appears a promising solution to provide reconfigurable data paths to adapt to the varying traffic patterns [3]. OpenFlow [4] provides a fixed non-programmable match and action structure with a close set of protocols and fields to configure a data plane. However, it is getting over complicated in an attempt to cover every possible protocol, whereas new approaches offer frameworks to program the data plane using high-level languages and compiling on a target network card or node, including ClickNP [5], OSDF [6] or Emu [7]. P4 [8] has become an appealing alternative being adopted by academia and industry, as it is a common language for the description of data plane functionalities of different targets. However, not every hardware architecture can support every language option defined in P4, which reduces the portability. Moreover, to add flexibility to describe non-standard elements available in a concrete target, the language provides mechanisms to add external modules to the pipeline. There is an official P4 compiler, P4C, which is target-agnostic and is used as a showcase of the P4 functionalities. P4 requires a target architecture, a structure with fixed elements and programmable modules. The Portable Switch Architecture (PSA) is a popular target architecture that describes

common capabilities of network switch devices, which process and forward packets across multiple interface ports with a pipeline of three input stages (parser, ingress and deparser) and three output stages (parser, egress and deparser). There are multiple compilers available for different target technologies, using the PSA, or a modified version such as FPGA [9], [10], Network Processor Units (NPUs) [11] or Application Specific Integrated Circuits (ASICs) [12].

These reconfigurable solutions have been employed to implement multi-tenant programmable support with VXLAN using a NPU [13], ASIC [14] or FPGA [15]. They have been employed to implement Long-Term Evolution (LTE) traffic with the General Packet Radio Service (GPRS) Tunneling Protocol (GTP) using hardware-accelerated switches [16]. Moreover, Deep Packet Inspection (DPI) to classify the traffic and selectively apply actions to application flows has been implemented over GTP using software solutions [17] and NPU [18].

Regarding software-based solutions, a user-space module used for low-delay filtering of streams available to the mobile user has been proposed [19]. It employs a function on an access router that manages the mobility signaling for a mobile node that is attached to its access link. This approach is implemented within the context of the LTE Evolved Packet Core (EPC) and no multi-tenant isolation is discussed, and thus nested encapsulation is not considered. Other approaches try to implement GTP decapsulation and re-encapsulation software to allow the use of traditional IP hardware-acceleration [20]; however, this removes the support for user mobility, which is a significant drawback.

Salva-Garcia et al. [21] propose the only framework found in the literature that is able to work in a multi-tenant 5G network data path based on Netfilter, thereby achieving traffic control over Edge-to-Core using a set of hooks inside the Linux kernel to provide callback functions for every packet that traverses the respective hook within the network stack. However, this approach is a software-based solution where the inclusion of new rules leads to an increase of the overall latency for all the traffic passing through the kernel.

From the hardware side, Attig and Bredner [22] present a programmable FPGA-based parser that achieved high throughput at the cost of high latency. It uses a simulator to validate the operation of the Xilinx Virtex-7 FPGA employed. The work focuses mainly on nested tagging protocols (VLAN and MPLS) but lack of support for nested encapsulation headers. Consequently, that solution is not suitable for the 5G Edge-to-Core network segment concerned in our work. In [23], an FPGA-based parser has been implemented using Xilinx Virtex-7 in an SDN architecture. Better performance results are reported compared with [22] in terms of latency but the solution does not provide support for nested encapsulation of 5G traffic either.

In [24], a hybrid hardware-software solution proposes a way to increase the performance in 5G mobile traffic. This solution employs DPDK [25] yet only leverages software acceleration to classify 5G packets between the different CPU cores using a hashing function to identify the correct worker core. Although the solution in [24] presents excellent values in terms of throughput, the average latency reached is 70 microseconds,

4 times slower than our hardware acceleration based solution presented in this paper.

The solution in [24] is tested in a real 5G edge-core environments; however, the work does not provide any scheme to control traffic in the network, which in turn imposes a significant penalty in overhead in contrast to our research work. Therefore, in that solution no performance analysis has been carried out through performing real flows control and management. Our solution instead provides a REST API that allows flows control and management to be programmed in hardware to avoid increasing in latency. Our solution has also been tested in a real 5G environment, and moreover in our case, we have tested the environment using 4K Ultra High Definition (UHD) videos and inserting and removing rules to adapt the quality of the video to the requirements of the 5G users.

Despite the above advances in the state of the art, there is no existing hardware-accelerated solution that is able to support the nested encapsulation introduced by 5G multi-tenant networks whereas allowing programmable traffic control. This gap in the state of the art has been the main motivation for this research work, which provides a prototype of a FPGA NIC with nested encapsulation support for hardware acceleration suitable for 5G Edge-to-Core network segments.

3. Proposed FPGA-Accelerated Multi-Tenant 5G Architecture

This section describes our proposed architecture to achieve an FPGA-accelerated multi-tenant 5G network data path for the Edge-to-Core network segment.

3.1. Architecture Overview

Figure 1 depicts an overview of a 5G infrastructure that has been deployed in our premises using a MEC architecture based on OpenStack with multi-zone support. Figure 1 shows different architectural components and network segments associated to different geographical locations. The management node and network with the OpenStack Controller has been omitted for the sake of simplicity. The fronthaul defines the segment between the UE and the Remote Radio Head (RRH) located on the top of the mast and attached to antennas. To reduce costs, 5G networks are expected to be based on a Cloud-RAN (C-RAN) deployment where multiple RRHs are connected to a pool of BaseBand Units (BBUs) through optical fibres. In a MEC architecture, these BBUs are deployed in the last mile, close to the UE to allow also the deployment of fast processing data services collocated with the BBU at the edge of the network. The 5G architecture is based on the functional desegregation of all the existing 4G/LTE services to allow a flexible deployment of such functionalities in different network segments according to the requirements of the customers. Thus, to represent graphically this functional desegregation, RRHs and BBUs are usually depicted in 5G terminology as Distributed Units (DUs) and Centralized Units (CUs) to indicate that the roles of these units will depend on the specific deployment [27]. The deployment in our

premises uses OpenAirInterface [28] as part of the LTE/5G infrastructure deployed using Ettus B210 [29] Software-Defined Radio and SIM Cards from SYSMOCOM [30].

This paper focuses on the network segment between the edge and the core. This network segment is governed by OpenStack to allow multi-tenancy isolation of the different virtual machines (VMs) that are deployed at either the edge or the core network locations. This multi-tenancy is achieved at the production stage using either a tagging protocol such as VLAN or an encapsulation protocol such as VXLAN, GRE or Geneva, depending on if the cloud provider allows its customer to have software-defined networks or not. This encapsulation is implemented currently either at software layer using a virtual switch such as Open VSwitch (OVS) [31] or at hardware layer using Single Root I/O Virtualization (SR-IOV) [32] with VLAN tagging support, or similar technologies. This multi-tenancy support allows the sharing of the same physical resources by employing virtualization and encapsulation between different tenants (typically corresponding to different operators) whilst imposing this encapsulation requirements. Our deployment employs OVS v2.6 [33].

The LTE Serving Gateway (SGW) has been functionally disaggregated into the User Plane Function (UPF) in 5G, acting as a mobility anchor of the communications for all the users towards the core network. The communications between BBU and SGW represent all the uplink/downlink traffic sent/received by the users that are not connected to the same antenna. These communications are encapsulated using the GTP protocol, mainly to allow the management of the mobility of the users across the different antennas in a transparent way without losing connectivity while a user is being handed over between different RRHs. This encapsulation is applied by both ends of the data path, i.e. BBU/CU and SGW/UPF. It is important to note that the merging of both 5G and MEC architecture in a production-ready environment will entail the usage of a network traffic pattern with double encapsulations to support both multi-tenancy and user mobility simultaneously. It is expected to have traffic with GTP over VXLAN and GTP over GRE along this Edge-to-Core network segment. GTP encapsulation is performed by the BBU/CU and SGW/UPF software services whereas VXLAN [5]/GRE [6] encapsulation is performed by the virtual switch. After these double encapsulation is performed at various stages along the data path, the packets are sent to the Linux kernel stack and then to the NIC using Direct Memory Access (DMA) by its driver and finally processed by the NIC to be delivered to the other end, either Edge to Core or vice versa.

A new FPGA-based NIC prototype is devised in the proposed architecture to enable the experimental programmability of the hardware data path. This new prototype demonstrates the suitability of the proposed support for the novel classification of the 5G traffic within the double encapsulation to allow the programmability of the 5G multi-tenant data path between the Edge and Core network segments. The following subsection presents this FPGA-based NIC prototype.

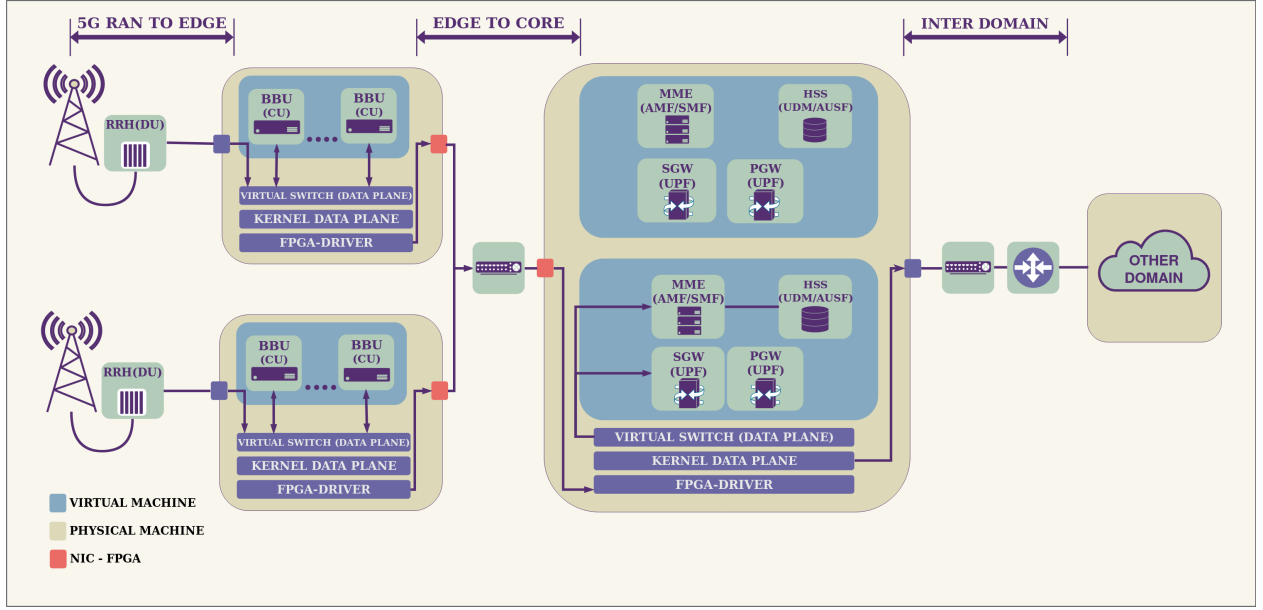


Figure 1: Overview of the proposed FPGA-accelerated multi-tenant 5G architecture

3.2. Data Path Hardware/Software Framework

Figure 2 shows the architecture of the FPGA-based data path prototype. The FPGA-based NIC used as a reference to implement the proposed prototype is the NetFPGA SUME [40]. This programmable FPGA NIC provides 4 x 10GbE ports and 1 DMA port (for NIC-to-Kernel communications) that are later connected to Rx and Tx queues to homogenize the different clocking times.

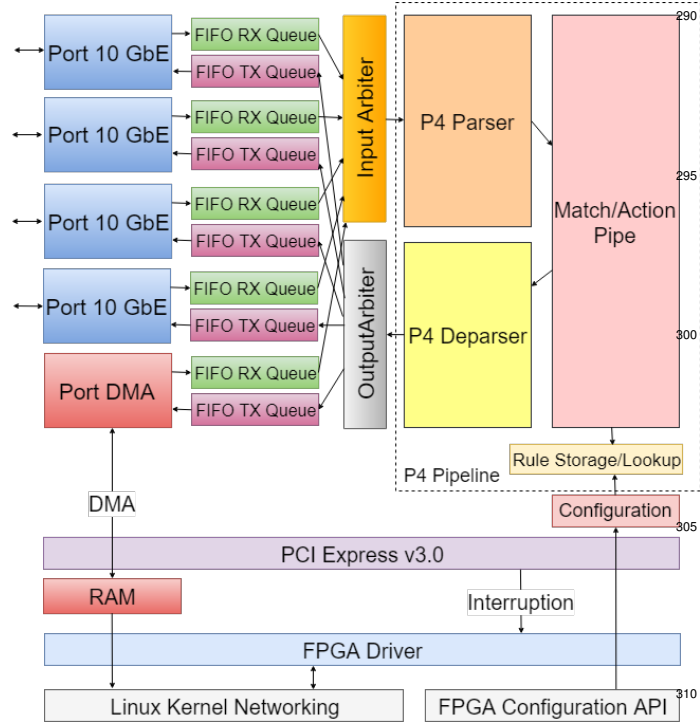


Figure 2: Pipeline of reference P4 NIC hardware/software data path.

As shown in Figure 2, all the packets being received in the RX Queues are served using a Round-Robin algorithm implemented into the Input Arbiter to the P4 Pipeline. As a reference prototype, it has employed the P4 NetFPGA reference implementation recently released by the NetFPGA Team [34] using the Xilinx SDNet P4 compiler [35]. This generic P4 pipeline is composed by three sequential stages: Parsing, Match/Action and Deparsing. The role of the parsing stage is to provide a custom packet classification capability to extract all the desired information of the packet. The role of the Match/Action stage is to allow the programmability of the actions to be conducted over the packet by matching the extracted information in the parsing step against values stored in a lookup data structure. Finally, the role of the Deparser stage is to reconstruct the packet (if required) following the actions indicated by the Match/Action step and thus sends it into the Output Arbiters. The output Arbiter places the received packets into the appropriate TX queues following the indication received by the Deparser. If the packets are intended to be received by the computer where the NIC is installed, they follow the DMA path, which performs a direct copy of the packet in RAM, using the PCIe v3.0 interface, and then notifies the NIC FPGA-driver of the reception of the packet to allow the process of the packet in the kernel of the operating system.

3.3. Proposed 5G Multi-tenant P4-Based Data Path

The data path proposed mainly acts in the first two stages of the NetFPGA P4 pipeline: Parsing and Match/Action. Figure 3 shows the logical representation of the two stages of the pipeline that have been designed in our prototype to provide native support for the double encapsulation required in the Edge-to-Core communication within the multi-tenant 5G networks.

3.3.1. Parsing Stage

Regarding the P4 matching stage (the upper part of Figure 3), a specific P4-based program has been developed to allow the desegregation of IP flows, LTE/5G flows, multi-tenant VXLAN flows and 5G flows nested in multi-tenant VXLAN flows, respectively. These flows arrive as incoming packets at the pipeline and they are processed using a data-driven programming approach where every header is sequentially processed to extract the key interested values that are going to be used to apply rules in the Match/Action stage and to determine what is the next header to be processed based on key header fields available in the headers. For example, to move from Ethernet Header to IP Header (P1 in Figure 3), the field Ethernet Type of the Ethernet header is checked against the hex value 0x0800 indicating that the next header type is IP. To identify the encapsulation protocols that are supported in this pipeline, a lightweight approach has been designed to check mainly the UDP port value (P2 in Figure 3) against their standard usage indicated by IANA [36] rather than going for more complex DPI approaches in order to minimize delay. This approach allows classifying GTP and VXLAN, which are the main protocols implemented to validate our design. Specifically, VXLAN uses UDP 4789 whereas GTP uses UDP 2152. It allows continuing the parsing of the packets into the tenant network in case of VXLAN or into the UE network in case of GTP. 5G networks will impose the usage of both VXLAN and GTP, one over the other; therefore, this identification process of encapsulation protocols is performed for various times along the pipeline in order to allow a really fine-grained definition and desegregation of traffic per tenant and per user. It is noted that after the first UDP header (P2 in Figure 3), the encapsulation ID is extracted from the encapsulation protocols. This ID has the main purpose of identifying a specific set of traffic. For example, it is used to tag the tenant ID in case of the MEC multi-tenant architecture (K4 in Figure 3) and to tag the UE traffic in case of the 5G architecture (K5 in Figure 3).

The Real-Time Transport Protocol (RTP) is used to multiplex different audio and video traffic within the same flow, allowing the video/audio player to have synchronized information to be played in real time. This protocol has been added to this design to provide support for the use case that has been prototyped in the empirical validation. RTP will stress even more the design since it provides another level of flow desegregation where different audio and video flows are multiplexed in the same network flow. In summary, key values are extracted from RTP and its payload to identify to which video/audio sub-flow this packet is associated within the same RTP flow. K6 in Figure 3 indicates where the RTP payload is extracted to identify the type of sub-flow, and K10 and K11 indicate where the video quality and temporal layers IDs are extracted to know what quality and temporal layers a video flow are associated to, respectively. These video layer meta-data are extracted from the Scalable H.265 video codec [47], [48], which is the latest video codec, to determine which layer can be removed to reduce the resolution or the frame rate of a given video flow to be able to adapt the video in network congestion conditions by

removing less important video layers (more details in section 5). One of the challenges associated to the classification of the RTP is that DPI needs to be performed to identify correctly that the payload is an RTP payload. To this end, an adaptation of the DPI classification algorithms for RTP implemented in nDPI [37] is explored to check the value of the first 6 bytes of the payload against a specific mask shown in Figure 3. RTP has been implemented in the same way as it is considered as a special type of encapsulation protocol (for video traffic). It will validate an architecture where even triple encapsulation is present (i.e., RTP over GTP over VXLAN).

Regarding the approach for parsing encapsulation, it is noted that K4, K5 and K6 in Figure 3 appear more than once in Figure 3. This is because the information about these headers can be extracted from different parts of the packet depending on the number of encapsulation protocols that are present in the packet. Thus, to deal with this dynamic nature, it has been decided to create three extra fields of meta-data that indicate what is the encapsulation type associated to that value extracted. This provides the semantics of such a value (K7, K8 and K9). These meta-data take the values of VXLAN, GTP or RTP in order to provide the semantics of the values stored (K4, K5 and K6). This is a clear extension to the state of the art to allow the support of nested protocols. This dynamism in the classification of the packet is a clear differentiating point of our proposal with respect to traditional firewalling/filtering appliances that do not allow more than one occurrence of the headers.

Regarding the approach for parsing the IP addresses, it is noted that K1 appears more than once in Figure 3. This is because the information about this header can be extracted from different parts of the packet depending on the number of encapsulation protocols present in the packet. Consequently, the semantics is completely different, and every IP header detected will override the value of the previous IP header extracted so that at the end of the parsing, only the most inner IP header information will remain available in the meta-data extracted.

It is noted that the support for these three different types of encapsulation in any order together with the extraction of the most inner IP header information allows the NIC to classify and perform actions over every video layer delivered/received from a UE moving between antennas. These antennas can belong to different tenants of the MEC architecture, where the traffic is isolated to enforce isolation between tenants while they share the same computational resources. This capability allows the definition of fine-grained rules in the Edge-to-Core segment, which has never been supported before.

In Figure 3, three different names are used to refer to the flows according to the number of encapsulation protocols associated, namely, IP Flow, Multi-tenant Flow (VXLAN), LTE Flow (GTP), and 5G Multi-Tenant Flow (GTP over VXLAN). These names will be used in the rest of the paper to refer to different packet traces (traffic patterns). It is noted that K3 in Figure 3 is the only value that is used in the rule, but it is not extracted from the packet. This is a counter that is increased every time when there is a new encapsulation header. It will match the values 0, 1, 1 and 2, respectively, with these four types of flows described. It allows determining the mask used in the ac-

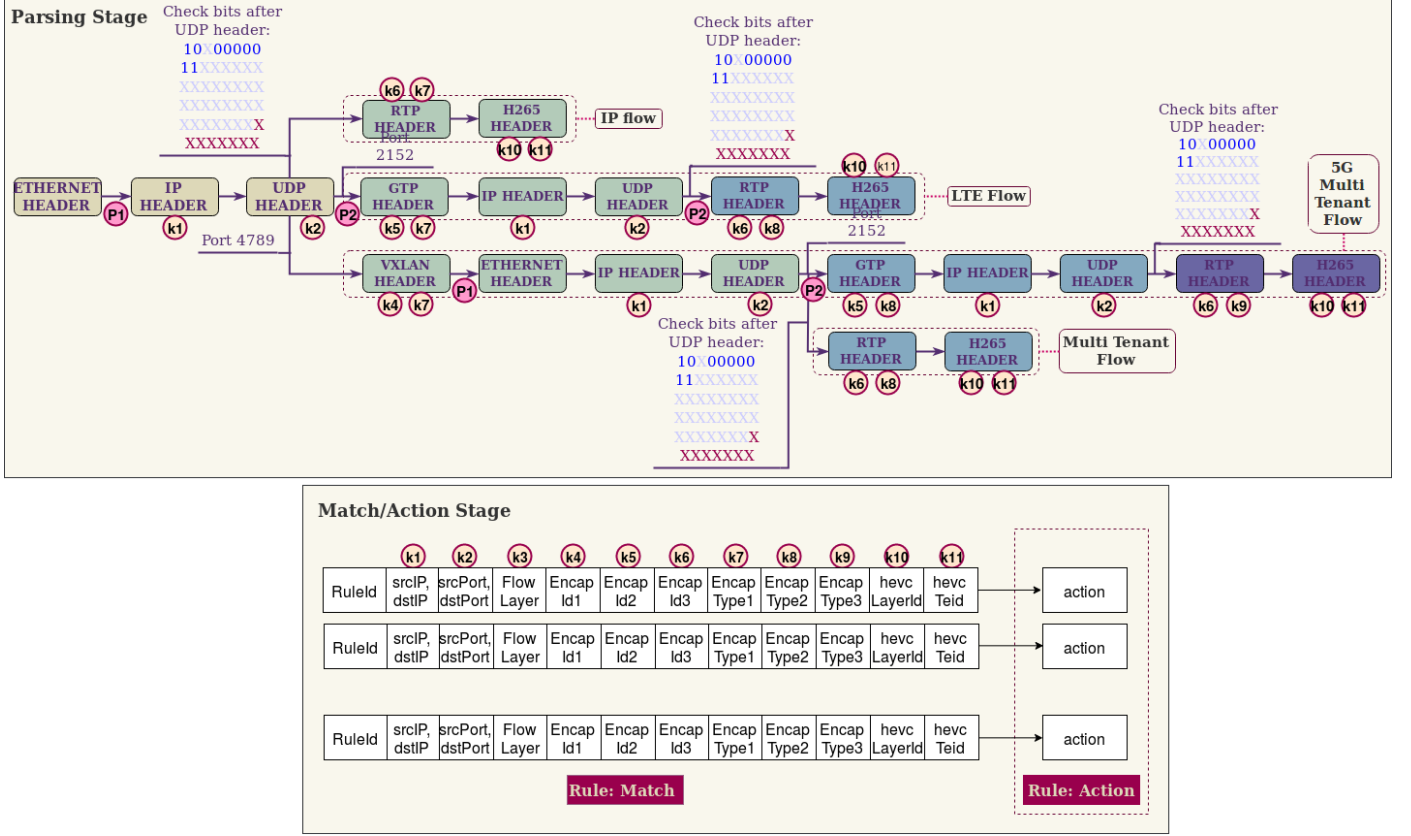


Figure 3: Design of the 5G multi-tenant match/action data path

tion stage to be calculated dynamically rather than statically as happening in most of the architectures today.

As addressed in [38], the inclusion of nested encapsulation fosters packets fragmenting, as there are several IP layers. There is no existing standard strategy for fragmentation in this scenario. Our solution provides mechanisms to detect fragments at any of the encapsulation layers, providing coherence in the decisions made over a packet to all its fragments.

3.3.2. Match/Action Stage

Once the parsing stage has been performed, all the meta-data are extracted from the packet and then shared with the Match/Action stage. In fact, in the lower part of Figure 3, it can be seen that the structure of the designed rule to clearly identify what are the key field extracted from all the headers along the way, e.g., IP addresses, encapsulation IDs, encapsulation types, UDP/TCP ports, and video layer information. These meta-data are used to match the extracted information against a list of rules stored in a data structure, allowing fast matching and recovery of the positive matching. If there is a positive matching, the first matching result will provide the action to be conducted over the packet. Currently, three different actions are designed, useful in the context of the Edge-to-Core segment: DROP packet, L1 MIRROR packet and L2 REDIRECT packet, allowing implementing several use cases such as selective monitoring [39], self-protection [40], intrusion response systems [41] and video optimization [21], among others.

Table 1: Functions to control ternary lookup tables

End Point	Description
/add	Adds a new rule in a table
/delete	Deletes a rule of a table
/clean	Deletes all the rules of a table
/numRules	Returns the total of rules

The usage of a list of rules implies the creation of a control channel to allow the insertion, deletion and update of rules into the data structure. To allow this functionality, the design explores the support from the P4 compiler project provided by the NetFPGA SUME prototype used. It allows the user to invoke an API to populate this list of rules from the user space of the operating system where the FPGA NIC is installed. A new API has been developed to enable the development of the scenario described before. It allows the control of the Ternary Content Addressable Memory (TCAM) tables where the rules are stored in the NetFPGA. The main functions are depicted in Table 1. The /add function of the API receives both matching and mask parameters to define the rule and the part of the rule that needs to be matched, together with the action to be performed in case of matching. This API allows the exposure of the control to enable the usage of the prototype in an SDN deployment where an SDN controller controls the rules along the data path.

4. Implementation

The selected framework for the based development of the proposed solution is the NetFPGA platform using the P4-NetFPGA compiler. This solution uses the NetFPGA Simple SUME Switch architecture, similar to NetFPGA PSA yet simpler. The reason why the NetFPGA has not been compared with other COTS cards is due to the expensive nature of FPGA cards in the current market and the lack of support for matching tables in existing COTS cards. The goal is to provide just enough features so that it is an effective prototyping tool. The implemented P4 represents exactly the design described in Section 3. The communication between the PC and the FPGA NIC is through PCIe, using the RIFFA framework [42], with support for PCIe v3.0. The RIFFA framework for NetFPGA is configured with one DMA engine of two bidirectional channels: one for packets and the other one for registers and configuration. On the PC side, the RIFFA driver configures one single PCI Base Address Register (BAR) and one interrupt for the communication, with support for four Ethernet interfaces (from nf0 to nf3). The Ethernet interfaces are linked to the packet channel, while ioctl calls are linked to register read/write and configuration. The framework provides an API and CLI to perform configuration operations from the user space to fill up tables and read/write registers.

Our solution uses tables to define the rules to perform actions on the encapsulated packets, using the values of specific fields of the incoming packet as key and specifying the rule ID and action to be performed as values of the table. In P4 NetFPGA, the tables are implemented using a pair of memory blocks: a CAM for the key detection and a RAM for storing the value. Depending on the capabilities associated to the matching pattern, the framework allows the selection of a regular CAM with exact matching pattern or a TCAM with ternary matching pattern support. Both CAM and TCAM allow a very fast retrieval of the first positive match of the given key against all the rules stored in the data structure. The main difference between them is that CAM forces an exact matching of all the fields that compose the key, whereas TCAM allows enable and disable if a field composing the key needs to be considered as part of the matching or not. It enables a significant flexibility in the design of the rules since now we can use wild cards in the definition of the rules to allow ANY semantics. For this reason, the prototype implemented has selected TCAM, using the Xilinx 1151 Application Note [43]. The regular CAM can be implemented using the reconfigurable LUT as shift modules (SRL16E) or using dedicated memory modules (Block RAM), both performing the reading in one clock cycle. The main differences are that the former requires 16 clock cycles for writing while the latter requires only two, and that the former uses reconfigurable logic that cannot be used for the P4 program logic. The TCAM can only be implemented using shift modules, reducing the amount of reconfigurable logic available for a P4 program. Our solution requires ternary tables to enable rules for the different encapsulation levels, considering different wild card usages depending on the scenario (optionally considering IP addresses at the different encapsulation layers, ports or application level headers).

Moreover, in a multi-tenant 5G scenario, there are packets with different encapsulation layers coexisting and thus the rules require the flexibility provided by ternary tables to ignore encapsulation layers that are not available.

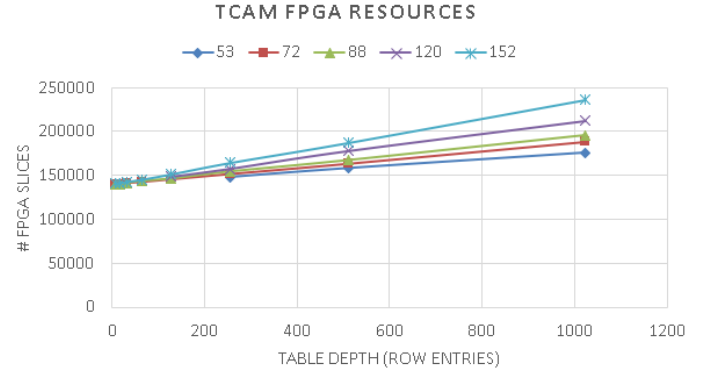


Figure 4: Slices used for TCAM.

Figure 4 shows the linear relation between key size, table depth and reconfigurable logic resources needed. We have selected a key size of 152 bits and a depth of 512, which allows us to insert 512 rules with different actions associated to each of them. Prior to the development of this data path for the NetFPGA, an efficient architecture needs to be designed, based on the TCAM implementation, to allow the identification of the 5G traffic. We have implemented three P4 programs for different NIC capabilities regarding the different traffic flows: an IP flow, a Multi-tenant flow (VXLAN), and a 5G Multi-tenant flow (VXLAN/GTP) supporting DPI at the application layer for video traffic over RTP classification. Nevertheless, the P4 program that supports 5G Multi-tenant flows is also able to support IP flows; in the same manner that the program to process 5G Multi-tenant flows is also able to process IP flows and Multi-tenant flows. The TCAM has been meticulously designed due to the fact that the storage capacity of the NetFPGA is strongly limited. As represented in Table 2, 98% of the resources have been used to develop the solution that supports the three types of flows. For this reason the selection of the keys shown in the Match/Action stage of Figure 3 has been carefully studied to select the lower number of fields that allow the detection of a specific flow.

Table 2: NetFPGA resources used in hardware implementation

	IP	VXLAN	VXLAN/GTP
Slices	55150 (51%)	74711 (69%)	106734 (98%)
BRAM	575 (39%)	793 (54%)	1240 (84%)

5. Empirical Validation

This section empirically validates the proposed approach, demonstrates the suitability of the proposed architecture for the 5G Edge-to-Core network segment, and provides an analysis of the scalability performance of the NetFPGA-based data path.

In addition, we evaluate the delay results to show how the proposed solution fulfills the 5G KPIs in terms of E2E latency.

5.1. Use Case Addressed

A realistic use case has been prototyped to empirically validate the effectiveness of our proposed architecture. In this use case, five 4K Ultra High Definition (UHD) videos are transmitted sequentially from a 5G UE to a server located in the Internet, outside of our administrative domain. In the communication, the video flows traverse from Edge to Core through our FPGA-based prototype, and then to Internet. The FPGA-based prototype is programmed to recognize and process the 5G multi-tenant traffic pattern. It is noted that the videos are encoded using Scalable H.265 [44], [45], which employs a layered coding mechanism to allow priority-based scalability in spatial, temporal or other dimensions. In Scalable H.265, the base layer video has the highest priority to be delivered, and additional enhancement layers can be discarded e.g., in response to network congestion.

In the testbed, the videos are encoded with two spatial video layers in 2K (based layer) and 4K (enhancement layer) resolutions respectively. The FPGA prototype is programmed to recognize and then drop the 4K video layer of all the video flows. This use case has significant implications since it is expected that 90% of traffic in Internet will be video traffic in 2020 and 5G is not an exception [46]. The dropping of less important video packets from a video stream is a typical adaptation mechanism to deal with transmission constraints such as network bandwidth limitation caused by traffic congestion.

When the traffic is passing through the network segment between Edge and Core, three different encapsulation scenarios are analyzed. Firstly, a traditional IP network with no encapsulation is set up to establish a reference baseline for comparison. This scenario employs a network traffic stack defined as MAC/ IP/ UDP/ RTP/ VIDEO Layer Payload. Secondly, a MEC scenario has been analyzed where multi-tenancy has been employed to isolate tenant traffic. This scenario is defined as the following network stack: MAC/ IP/ UDP/ VXLAN/ MAC/ IP/ UDP/ RTP/ VIDEO Layer Payload. Finally, to achieve a performance evaluation in a 5G multi-tenant infrastructure, both VXLAN tunneling for tenant isolation and GTP for UE mobility across different antennas are included. This scenario adopts a network traffic stack defined as MAC/ IP/ UDP/ VXLAN/ MAC/ IP/ UDP/ GTP/ IP/ UDP/ RTP/ VIDEO Layer Payload.

To achieve reproducible lab conditions, the video transmission for the double encapsulation is first sent from a 5G UE using an architecture analogous to the one depicted in Figure 1, currently deployed in our lab, as part of our roadmap to achieve a 5G trial in our premises. Then, a PCAP (Packet Capture) file is generated from this infrastructure to allow us to scale up the number of flows using PCAP processing tools, and to remove the encapsulation to gather comparable yet simplified scenarios such as the simple encapsulation (Multi-tenant flow) or the one with no encapsulation indicated (IP Flow). These PCAP files are then used in our experimental setup to validate both the performance and scalability achieved in the prototype.

5.2. Experimental Setup

Figure 5 depicts the experimental testbed constructed to carry out the empirical validation of the proposed framework. Both Edge and Core Cloud Compute share the same hardware specifications: Dell T5810, Intel Xeon CPU E5-2630 v4 2.20GHz, 32768 MB RAM, and 512 GB SDD. In terms of network cards, the Edge compute has a Gtek MLX-6801-1S 10GbE NIC with 2 x 10GbE Interfaces whereas the Core compute has a NetFPGA SUME [47] with 4 x 10GbE Interfaces. The NetFPGA has been programmed with the pipeline with support for 5G Multi-tenant flows and all the experimental results have been gathered using such FPGA bitstreams.

The testbed is governed by an Experiment Script that ranges the number of 5G video flows to measure scalability, packet size, packet rate and the type of video flow (IP flow, Multi-tenant flow, 5G Multi-tenant flow) to measure performance in terms of delay, packet loss and throughput. Table 3 shows the ranging values of each of the different dimensions empirically analyzed.

For each of the scenarios analyzed, the Experiment Script inserts the rules associated to the scenario that is going to be processed (see 1 and 2 in Figure 5). There is a maximum of one rule per video flow and the main action associated to the video flow is to drop the enhancement layer of the video flow. Later, the Experiment Script starts a tcpdump in the receiver interfaces in the Edge side and after that starts sending the PCAP to the Core compute (see 3 in Figure 5). The FPGA NIC is programmed with the proposed framework. Packets are sent from the Edge and received in the prototyped network card in the Core network segment and all the packets related to the enhancement video layer are then dropped. The rest of the packets are sent to the FPGA driver of the Core compute, reaching the Linux operating system and thus the VMs running there. All these packets will be mirrored by default to another NIC interface of the FPGA. This mirroring is an artefact designed in our testbed with the main intention to be able to measure end-to-end network delay using a common reference clock. Then the packets are received back to the Edge compute and stored in a PCAP to be later processed in a batch mode off-line. This saving of both sent and received PCAPs is only used to later on calculate the delay using the same clocking reference. The measurement of packet loss and throughput do not require the usage of this artefact. This process has been executed five times in order to show statistical significance. One hop has been deployed between the Edge and Core, as a realistic scenario where CU and UPF will be deployed.

After the scenarios are executed, all the PCAPs are stored in the Edge computer. Then, the Data Processing Script is executed to analyze both the sent and received PCAPs, calculating end-to-end delay, the number of packet dropped, and bandwidth saved due to the application of the rules. The empirical results achieved in this testbed are described in the following subsections. Different experiments have been carried out as described in the following subsections.

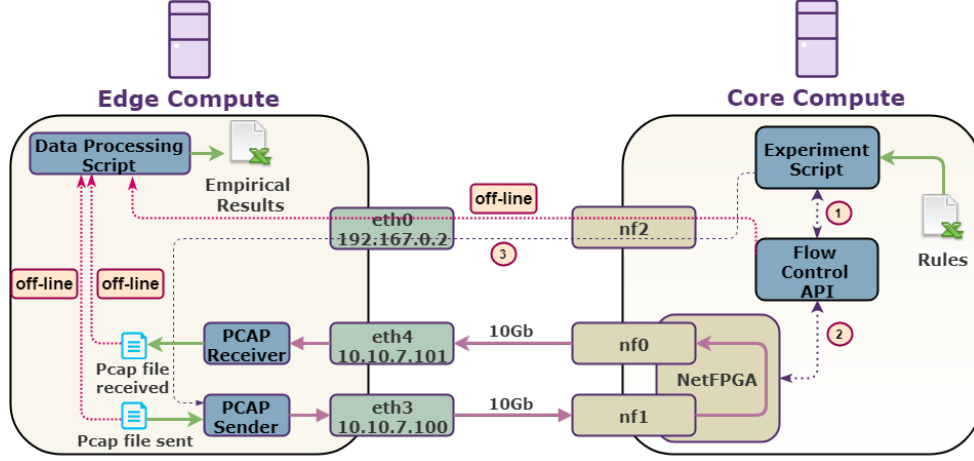


Figure 5: Testbed for empirical results over the prototyped architecture.

Table 3: Testing parameters

Dimension	Min	Max	Steps
# 5G Video Flows	1	512	1, 2, 4, ..., 512
MTU	150	1500	150, 200, 250, 300, 400, 500, ..., 1500
Bandwidth (Mbps)	1000	10000	1000, 2000, ..., 10000
Type of Flow	IP	5G Multi-tenant	IP Flow/Multi-tenant Flow/5G Multi-tenant Flow
# Rules	0	512	0, 1, 2, 4, ..., 512

5.3. Pipeline Evaluation Test

The main purpose of this section is to validate the proposed design by analyzing the delay introduced in the pipeline due to the extra logic required to provide support for the classification of the different encapsulation layers present in the packets. Figure 6 plots an analysis of the delays for the different bitstreams programmed in the NIC. Three different bitstreams have been programmed in the NIC with support (1) only for IP flows, (2) for IP flows and VXLAN flows, and (3) for IP flows, VXLAN flows and 5G Multi-tenant flows, respectively. Then, for each of the programmed bitstreams, different PCAP files have been inserted in the pipeline to examine their difference in terms of delay at line rate speed of 50 Gbps for the pipeline. Figure 6 shows a white box analysis where the three main stages associated to the P4 pipeline are measured in terms of delay. Moreover, there is a fourth time measured directly related to the size of the packet, since the width of the P4 bus is 256 bits and thus only this number of bits can be processed in each of the cycle. Thus, for longer packets, there is an extra delay incurred due to the fact that they are crossing the pipeline. As can be seen in Figure 6, there is almost no difference in delay between the usage of one rule and the usage of 512 rules. This is mainly due to the key features associated to the usage of the TCAM structure (the left sub-figure in comparison with the sub-figure in the centre of Figure 6). Furthermore, there is a delay of less than 100 nanoseconds (ns) between very long packets (1500 bytes) and the shortest ones for double encapsulation (144 bytes) under the same conditions (the left sub-figure in comparison with the right sub-figure of Figure 6). The reason of this tiny delay is related to the fact that the implemented pipeline is able to process only 256 bits in each cycle and thus it will require more

cycles to process longer packets.

In addition, it is noted how the reference NIC only suitable for IP Flows requires around 3 microseconds to process the packet in the pipeline. In contrast, the NIC with support for single encapsulation (multi-tenant flows) requires 4 microseconds leading to a 1 microseconds of overhead in the pipeline to support this functionality. For the case of the support for double encapsulation, 6 microseconds are required to process the packet in the pipeline, i.e. there are 3 microseconds of overhead in the pipeline to support this 5G classification functionality when compared with the reference NIC. It is noted that any of the NIC implemented in this experiment behaves exactly the same for all the flow types that they support, as can be seen in the grouped bars shown in the figures. These results demonstrate significant effectiveness achieved in the programmability of this advanced processing of the pipeline for 5G Multi-tenant support. Table 4 shows the specific numerical values plotted in Figure 6.

This 3 microseconds of overhead of the proposed solution contributes minimally to the E2E latency by adding only 0.003% to the 1ms 5G latency KPI imposed by NGMN; meanwhile, in reward, this minimal overhead enables us to achieve programmable traffic control capabilities over a new infrastructure with user mobility and tenant isolation, leading to improved infrastructure protection and access control, traffic engineering, QoS management, etc. It is noted that current reference NIC only provide some of these capabilities for pure IP network and not for 5G multi-tenant networks.

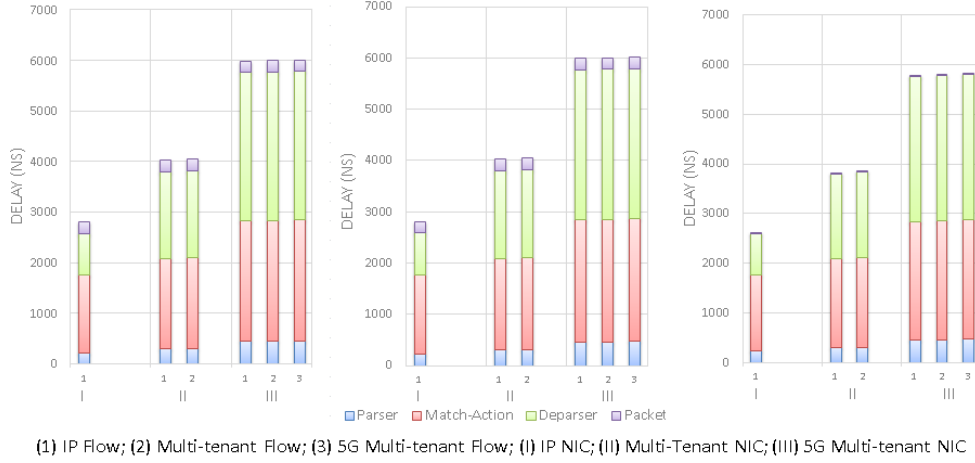


Figure 6: Analysis of delay in the pipeline for the different bitstreams programmed in the NIC versus the type of flow being processed in the NIC. (Left) 1 Rule and 1500 bytes packet size, (Center) 512 Rules and 1500 bytes packet size; (Right) 1 Rule and 144 bytes packet size.

Table 4: Analysis of the delay results plotted in Figure 6 (in microseconds) about the pipeline of the different bitstreams programmed in the NIC against the types of flows supported for each bitstream.

	IP Flow	5G Flow	5G Multi-tenant Flow
1 Rule, 1500 MTU	2,9	4	6
512 Rules, 1500 MTU	2,9	4	6
1 Rule, 144 MTU	2,8	3,9	5,9

5.4. Performance Test

The performance experiments have the main aim to empirically validate and evaluate the prototype in different conditions using the testbed described in section 5.2. The results obtained in this paper are not empirically compared with other solutions due to the fact that there is not any other FPGA cards in the market with programmable 5G Edge-to-Core support yet and thus no results can be obtained.

As initial testing, sending bandwidth is linearly increased with no rules inserted in the TCAM structure to focus on the evaluation of the NIC performance. The intention is to measure the evolution of the end-to-end round-trip delay, packet loss and throughput, whilst the packet size is linearly decreased from the Ethernet Maximum Transmission Unit (MTU), which is 1500 bytes. This experiment is carried out against the three types of flows considered: IP Flow, Multi-tenant Flow and 5G Multi-Tenant Flow, to analyze the behavior of the implemented P4 pipeline for the Edge-to-Core 5G multi-tenant flows under different PCAPs.

The first aspect to analyze is the maximum throughput that can be achieved using the standard Gtek Mellanox ConnectX-2 MLX-6801-1S 10GbE NIC to send and receive PCAPs from the NetFPGA card with the latest version of the Mellanox Linux drivers provided for the card, v.4.2-1.0.1.0 [48]. To do so, an iperf stress test has been carried out using a loopback interface and tcpdump to store both sent and received PCAPs. The PCAPs are stored on a fast PCIe SSD-drive Toshiba THNSN 5512GPU7. As a result, we have empirically measured the

maximum throughput achieved in our testbed to be up to 3,8 Gbps, as depicted in Figure 7. Beyond this throughput, the network card starts to drop packets in the transmission and then the network conditions cannot be measured accurately. Moreover, the 3,8 Gbps throughput is further reduced to 3 Gbps due to the employed packet capturing. This is the reason why all the experiments range speeds up to 3 Gbps, a practical maximum throughput, even with a nominal 10 Gbps interface. Moreover, the throughput is largely dependent on the size of the packets used in the experiment, mainly due to the number of interruptions associated to each packet that need to be processed by the NIC driver. Thus, with packet size of 1000 bytes, an empirical maximum of 1.4 Gbps can be achieved. These numbers are even worse for small packet sizes, and the worst scenario is for a packet size of 150 bytes where the maximum throughput is around only 180 Mbps.

Figure 8 shows the behavior of the prototype with support for 5G Multi-tenant flows in terms of end-to-end delay and packet loss ratio for the three types of flows concerned. The IP Flow case has been included as a reference baseline and sub-figures a) and e) show the delay and packet loss ratio respectively. In terms of delay, it is worth mentioning that there is a constant trend related to the end-to-end delay measured around 0.015 ms regardless of the throughput and packet size measured. It is worth noting how at high throughput and low packet size, there is a floor in the graph mainly due to the fact that the NIC has not been able to perform at this speed under this small packet size. In terms of packet loss, sub-figure e) shows a mountain shape which clearly saturates the packet loss ratio at a maximum of 49% for the worst-case scenario of 180 bytes of packet size and 400 Mbps throughput. To measure this packet loss ratio, the PCAPs being received have been sniffed in both Core and Edge computers and then analyzed off-line to derive the difference. This path includes driver transmission time, NIC transmission time, NIC reception time, DMA reception time and driver reception time. The mountain leaves two different valleys to each of its side. The left valley represents scenarios with no packet loss, allowing understanding what the

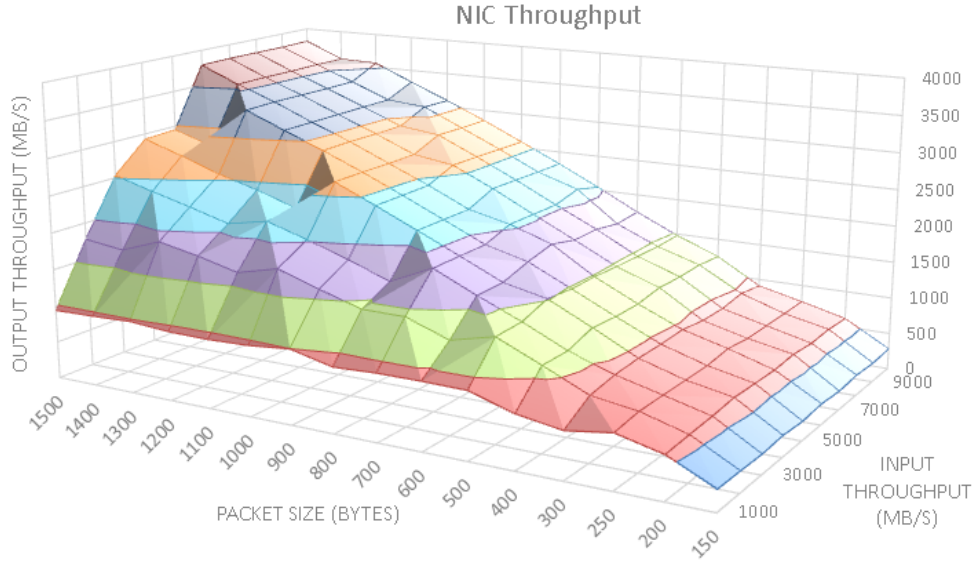


Figure 7: Sending throughput achieved in the empirical validation carried out to set up the maximum bandwidth used in performance test.

limit is until packet loss starts to appear. The right valley represents scenarios that have not been measured mainly due to the limitations on the sender side. Later, an analysis of the root cause of this high percentage of packet loss in high rate speeds is provided. For now, consider this performance as a reference baseline. When compared with a 5G Multi-tenant flow processed as depicted in sub-figures c) and f), it can be appreciated how both produce very similar results on each of the scenarios analyzed. This fact of delay between both cases shows an insight in terms of the potential performance of the proposed solution. It is noted how all the scenarios plotted, including the behavior of a multi-tenant flow (see sub-figure b) and e)), show equivalent results and the difference between them is on average less than 100 ns.

To understand the reasons of the low performance at high throughput, we compare the packet loss results previously calculated using PCAPs sent against PCAPs received in the Core computer (see sub-figure e) of Figure 8) with the packet loss results calculated in the Edge computer (see Figure 9). It is noted that there is another interface in the NetFPGA mirroring the traffic back to the sender to allow the measurement of the delay. This comparison will allow understanding the behavior happening in the path between the NetFPGA DMA channel and the Linux driver receiving the packets in the kernel space, since the other calculation of the packet loss does not use this DMA channel and just mirrors the traffic directly to another Ethernet interface.

The comparison between these two different results gathered about packets shows a significant bottleneck in the channel to the Linux kernel. It is noted that how the behavior of the packet loss is very similar in both sub-figure e) of Figure 8 and Figure 9. However, they do have a completely different scale: the packet loss ratio is close to 0.9% in the worst case of the scenario where the DMA channel is not part of the measurement, in contrast to the 45% of packet loss in the scenario where pack-

ets are sniffed in the kernel of the receiver after arriving at the Linux kernel. It shows that the adaptation of the RIFFA driver for the NetFPGA SUME project yields significant deficiencies to scale up higher bandwidths. Although DMA solutions are provided to send data from the card to the server offloading the CPU, the same CPU is interrupted constantly due to the amount of DMA interrupts. Several solutions are provided in high-end data rate solutions to overcome this problem, including IRQ affinity [49], interrupt coalescing [50], Receiver Side-Scaling in multi-core servers [51] or DPDK [25]. However, a deep analysis of the usage of CPUs under these scenarios has unveiled that the NetFPGA driver does not support such capabilities. In any case, avoiding traffic to the software stack reduces congestion in the driver bottleneck, for example programming flow actions directly on hardware.

6. Scalability Test

The scalability test has the main aim to empirically validate how the prototype behaves when scaling up the number of flows, rules and throughput. To this end, the MTU is set to 1500 bytes and the type of flow is a 5G Multi-tenant flow. The number of rules will match exactly with the number of flows for the sake of simplicity and the maximum number of flows has been set up according to the limitations of the size of the TCAM allowed by the physical programmable space of the FPGA chip used in the prototype, i.e. 512 entries. Five different videos are used, sending sequentially different flows of each one. Every flow is a 20-second 2K/4K Scalable H.265 encoded UHD video with 10 and 20 Mbps every video layer as average bitrate using variable bitrates.

The throughput is ranged using the same values of the previous experiment to make results comparable. Along this range of throughput values, the prototyped NIC is under congestion scenarios as indicated in sub-figure f) of Figure 8 for all the

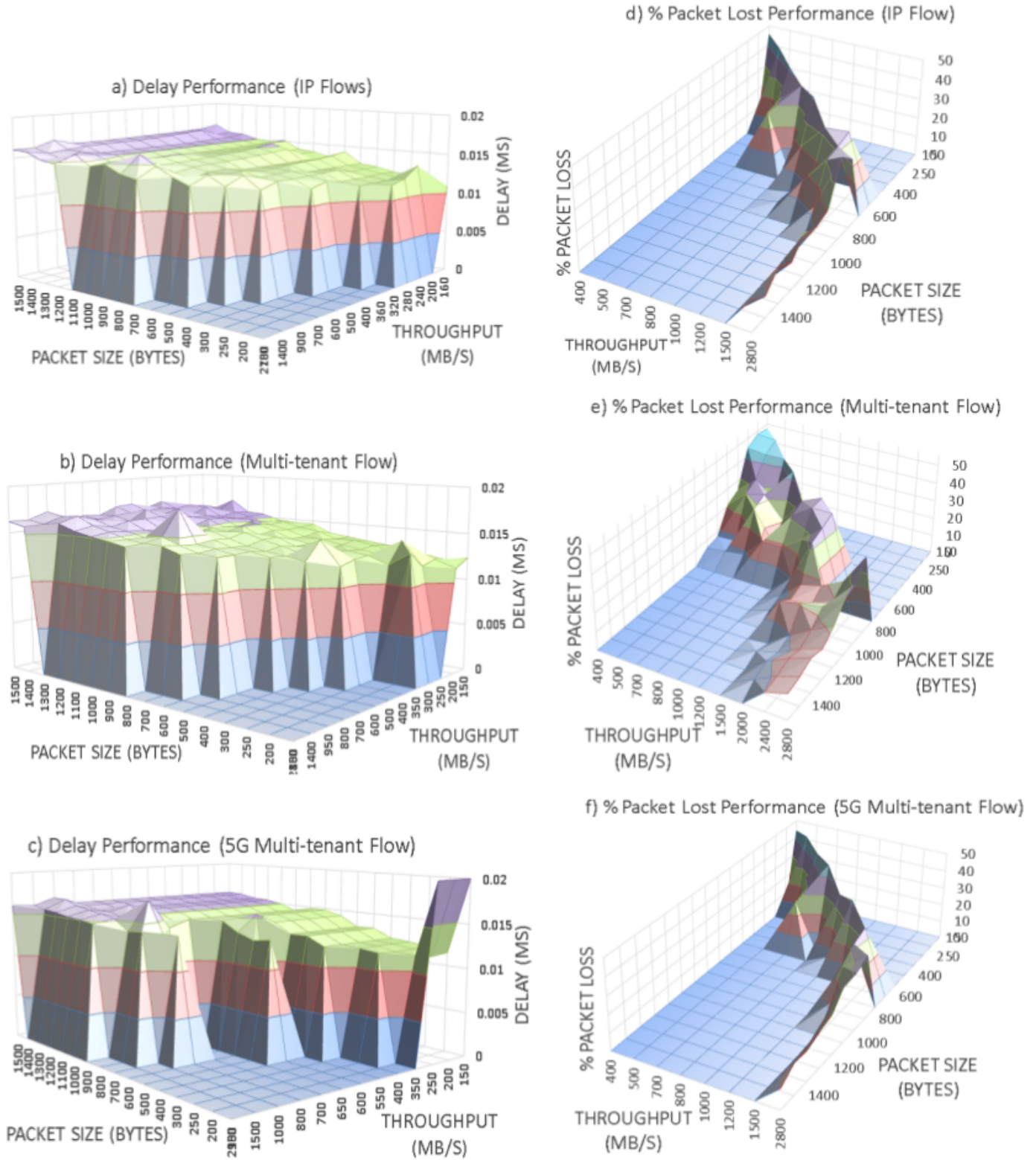


Figure 8: Analysis of prototyped NIC FPGA performance. a) end-to-end delay performance over IP flows; a) end-to-end delay performance over multi-tenant flows; b) end-to-end delay performance over 5G multi-tenant flows; d) % packet loss over IP flows; e) % packet loss over multi-tenant flows; f) % packet loss over 5G multi-tenant flows.

scenarios where packet loss ratio is higher than 0%. It is noted that the case for packet size of 1500 bytes of sub-figure f) of

Figure 8 is the base line to see how rules are used to reduce network congestion by dropping video layers. The application of

% Packet Lost (5G Multi-tenant Flow) without DMA

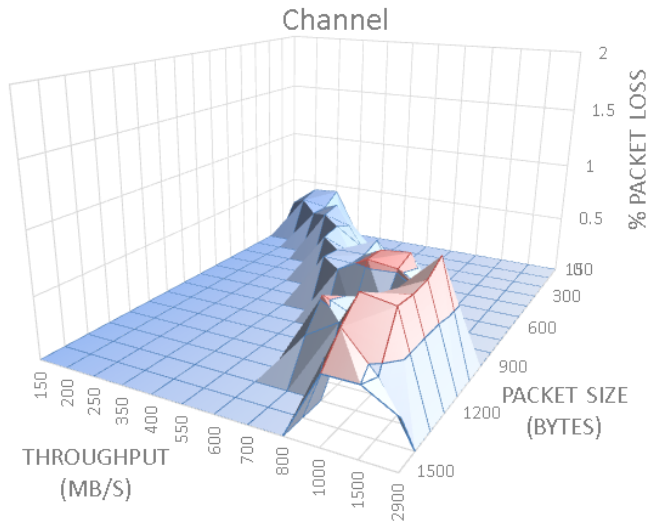


Figure 9: Analysis of % packet loss over 5G multi-tenant flow for the prototyped NIC FPGA when the DMA channel is not used to measure packet loss.

the rules will perform the dropping of the enhancement video layer of the video flows being submitted. Thus, the congestion will be mitigated by removing that enhancement video layer and the receiver of the video will only receive the video with 2K resolution rather than 4K, which in many cases a mobile user will not even notice the difference, specially if he/she is consuming the video from a 5G portable UE typically equipped with a screen of up to 10 inches. The evaluation of the impact of the perceived quality of the video delivered to the user is out of the scope of this contribution. Figure 10 shows the empirical results achieved.

% Packet Loss (5G-Multi-tenant Flow) vs # Rules/Flows

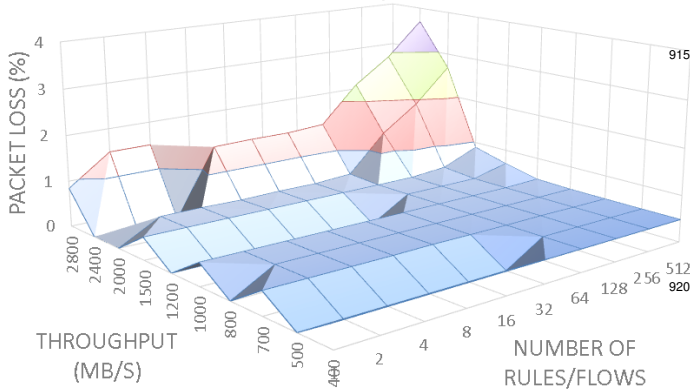


Figure 10: Analysis of % packet loss over 5G multi-tenant flow for the prototyped NIC FPGA when the DMA channel is not used to measure packet loss and using TCAM rules to drop packets.

As can be seen in Figure 10, the packet loss ratio along the communication between the kernel space of the Edge and the the kernel space of the Core computers has been significantly reduced due to the intentional dropping of packets being en-

forced in hardware, leaving the DMA channel under much less stress due to the significant reduction of the number of packets sent to DMA (only the base video layer at 2K resolution) since the enhancement video layer has been dropped in hardware using the hardware-based programming capabilities with the proposed support for 5G Multi-tenant video flows. Packet loss ratio reaches up to 4% in the worst case scenario where 512 flows and 512 rules are being processed at the same time. Figure 9 and Figure 10, both of which do not employ DMA, can be compared in terms of packets loss performance. Figure 9 shows that only 0,9% of the packets are lost when there is only 1 flow of 1500 bytes with a throughput of 2,9 Gbps. This value rises up to 3,7% of packet loss in Figure 10 when 512 flows and 512 rules are being processed, summing up a total throughput of 5,8 Gbps where 49.79% are dropped by the 512 rules and then 2.9 Gbps are forwarded. This difference in throughput processed is the main reason why packet loss is increased to 3.7%.

This reduction in the congestion of the network with a minimal impact for the Quality of Experience of the user is a clear added value to address the novel use cases and KPIs envisioned. This result shows the benefit of the proposed hardware-accelerated solution to address a very relevant scenario, which foresees video flows as the overwhelmingly dominating traffic in the coming years and is applied over the Edge-to-Core segment of the 5G MEC infrastructures. Moreover, as aforementioned, NGMN proposes an E2E latency KPI of 1ms for critical 5G communication. Our proposed programmable data path only contributes 0.02ms to this latency constraint. In contrast, traditional NICs would perform the classification of encapsulation via Linux kernel, which is not suitable to fulfill this ambitious 5G latency KPI. In fact, existing solutions based on software do not meet the strict requirements of the 5G latency KPI when traffic control is enforced in software. For example, in [21], a 5G traffic control flow framework is presented; however, it does not scale in terms of latency when more than 64 rules are applied, and resulted in a maximum of 25ms of delay when 512 rules are inserted. Our solution does not present any extra delay when the number of rules increases (as shown in Figure 6), and the values obtained fit totally the latency 5G KPI.

7. Further Discussions and Lesson Learned

After an extensive empirical experimentation and performance evaluation process, there are several lessons learned that are worth noting in this section. Firstly, the P4 language has been demonstrated to be a suitable approach to address the requirements imposed by the novel 5G and MEC architectures in general and by the Edge-to-Core segment, keeping the delays of the processing pipeline in very acceptable scales. Secondly, the experiments carried out have demonstrated the importance of the implementation of an efficient driver and an efficient kernel architecture in order to deal with the high packet rates imposed by the usage of the new high line rates speed envisioned for the coming years up to 200 Gbps or even 400 Gbps. Thirdly, along the execution of the empirical tests on the testbed, the measurement of the delay over the same reference clock required

significant machinery using the proposed approach of analyzing off-line the timestamps of the PCAPS for the sender and the receiver, although it has been demonstrated that it provides a good resolution up to microseconds. Fourthly, the amount of resources required by the usage of TCAM as data structure for storing rules impose a significant limitation in terms of energy and resources for scaling up the number of rules for various levels of magnitude. Therefore, it is important to research other mechanisms to make this scale-up feasible by exploring different (and efficient) ways to implement the data structure for rules. Finally, the scheme designed in this research allows the definition of 5G multi-tenant rules to perform a fine grained control of the new traffic workload patterns. The design of the values to be included in the rule to provide a high coverage of use cases in network communications has been a real challenge, especially due to the strong limitations in terms of key length imposed by the usage of TCAM.

8. Conclusion

Software-based networking technologies that underpin 5G networks could lead to compromised performance, which endangers the promised potentials of the next-generation mobile networks. To overcome this important problem, this paper has proposed a novel FPGA-based solution to accelerate the performance of the data plane in a 5G network, focusing on the Edge-to-Core segment. A new and insightful perspective into the new traffic patterns in the visualized, softwarized and multi-tenancy enabled 5G networks has been provided, leading to the design of the proposed 5G-aware traffic processing in the proposed system. The design and prototyping of the proposed system has been described in details, and the prototyped system has been experimentally tested and validated. A demanding ultra-high definition video application, encoded using the latest video coding standard, has been deployed as a testing use case to assess the real-time performance of the prototype. Extensive empirical results have shown that the proposed design and prototype has the potential to meet the challenging QoS requirements of the application in network congestion conditions by reducing the packet loss ratio from 49% to 4% in the worst scenario. The prototype has also demonstrated excellent scalability in terms of the number of rules for the match and action stage. It has been demonstrated that the support for 5G multi-tenant traffic only introduces an extra delay of just 4 microseconds, which is in line with the ambitious latency KPIs expected in 5G.

Future work will attempt to investigate the performance with programmable NICs of higher bitrates. Moreover, additional capabilities in 5G traffic engineering enabled by this approach will be explored. For instance, after the traffic classification different priorities can be assigned to support the service differentiation and QoS commitments in 5G networks for the users. This will allow further programmability in the data plane, which can enable distinguished 5G features such as network slicing in the data plane. In addition, future work will further investigate the acceleration of the 5G Cloud-RAN segment of the network, following the standard of IEEE 1904.3 [52] and the

specifications of eCPRI [53] to develop an NGFI [54] architecture, which allows a cooperative-mode operation between different elements of the network, leading to reducing the number of antennas needed to cover an area and increasing the uplink channel capacity.

9. Acknowledgment

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